THE RaDIATE HIGH-ENERGY PROTON MATERIALS IRRADIATION EXPERIMENT AT THE BROOKHAVEN LINAC ISOTOPE PRODUCER FACILITY*

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Abstract

The RaDIATE collaboration (Radiation Damage In Accelerator Target Environments) was founded in 2012 to bring together the high-energy accelerator target and nuclear materials communities to address the challenging issue of radiation damage effects in beam-intercepting materials. Success of current and future high intensity accelerator target facilities requires a fundamental understanding of these effects including measurement of materials property data. Toward this goal, the RaDIATE collaboration organized and carried out a materials irradiation run at the Brookhaven Linac Isotope Producer facility (BLIP). The experiment utilized a 181 MeV proton beam to irradiate several capsules, each containing many candidate material samples for various accelerator components. Materials included various grades/alloys of beryllium, graphite, silicon, iridium, titanium, TZM, CuCrZr, and aluminum. Attainable peak damage from an 8-week irradiation run ranges from 0.03 DPA (Be) to 7 DPA (Ir). Helium production is expected to range from 5 appm/DPA (Ir) to 3,000 appm/DPA (Be). The motivation, experimental parameters, as well as the post-irradiation examination plans of this experiment are described.

INTRODUCTION

One of the main challenges facing beam-intercepting components of future high intensity accelerator facilities is beam-induced radiation damage effects in materials [1]. To further understand how material properties evolve upon sustained interaction with high energy high intensity beams, an experimental study was initiated to investigate the radiation damage effects. Several materials used in critical accelerator components such as beam windows, secondary particle production targets and beam dumps, were irradiated with high energy protons to induce displacement damage and gas production effects, analogous to conditions in future accelerator complexes.

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IRRADIATION FACILITY

The primary mission of the Brookhaven Linac Isotope Producer (BLIP) facility at Brookhaven National Laboratory (BNL) is to produce medical isotope using 116 MeV primary proton beams. With the BNL Linac's capability to deliver protons up to 200 MeV, it is therefore possible to operate BLIP at higher energies and in tandem with material targets upstream of the isotope targets. In doing so, precise energy degradation through the target materials is required in order to deliver the optimal beam energy and proton flux to the downstream isotope targets to preserve isotope yield. As a result, significant fine tuning and multiple sensitivity studies were performed to optimize and configure the final target array composition.

A rastered beam with peak current of 165 μA and fluence of 7×10^{13} p/cm$^2\cdot$ s (3 cm diameter footprint) is delivered to the BLIP isotope targets. BNL also has hot cells and HEPA-filtered fume hoods available for PIE work with test equipment such as tension and 3-point/4-point bending fixtures, dilatometer, electrical resistivity fixture, X-ray diffraction at NSLS II, as well as photon spectra and activity measurements.

RADIATE IRRADIATION RUN

The 8-week irradiation experiment, performed in the framework of the RaDIATE collaboration [2], included various materials relevant to the participating institutions. Figure 1 shows the target box arrangement in the BLIP beamline, containing various materials just upstream of the isotope target box. The target box was configured in order to degrade the 181 MeV incoming Linac beam to the exact energy required for optimal isotope production. Each material type is enclosed in their individual stainless steel capsule, separated in series by a 2.5 mm wide gap of flowing cooling water.

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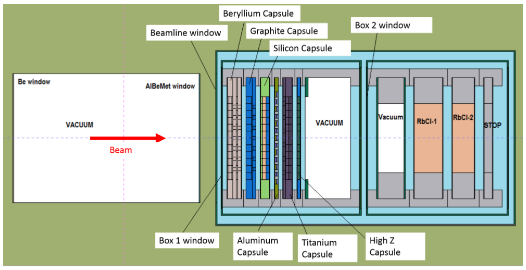

Figure 1: Targets arrangement in BLIP beam line.

PIE work, after sufficient cool-down time, will be carried out at various RaDIATE institutions to characterize strength, thermal and microstructural material property changes due to radiation damage effects. The motivation for and composition of each of the capsules are described in the following section.

SPECIMEN CAPSULES

Beryllium Capsule

Beryllium is a candidate material for proton beam windows and neutrino targets at Fermilab. Various grades (PF-60, S-65F, S-200F, S-200FH, and UHP) and types of specimens are included in the capsule, as shown in Fig. 2. The Be capsule is filled with Argon in order to impose the desired peak irradiation temperature of around 500 °C.

Figure 2: Beryllium capsule showing tensile and microstructural (left), bend (middle), and HiRadMat (right) specimens.

The HiRadMat specimens will be included in an experiment at CERN's HiRadMat facility to compare the thermal shock response of irradiated to non-irradiated specimens [3, 4]. PIE work of the tensile, bend and microstructural specimens will be performed at PNNL and University of Oxford.

Graphite Capsule

Graphite is the current material for neutrino production targets at Fermilab and other institutions. Different grades (IG-430, ZXF-5Q, Glassy Carbon GC20, and 3D C/C composite) and specimens types are included in a vacuum capsule, in order to achieve a high irradiation temperature (∼1000 °C) expected in future higher intensity neutrino production targets. As shown in Fig. 3, there are tensile, coefficient of thermal expansion, bend and HiRadMat specimens in the capsule. PIE work for the graphite specimens will be carried out at BNL, PNNL and CERN.

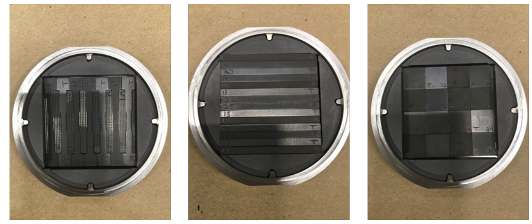

Figure 3: Graphite capsule showing tensile and CTE (left), bend (middle), and HiRadMat (right) specimens.

Silicon Capsule

Figure 4 shows the specimen layer arrangement in the vacuum-sealed Silicon capsule with estimated peak irradiation temperature of around 250 °C. The capsule contains Si bend specimen and SiC-coated graphite discs, candidate materials for the CERN SPS internal dump and KEK muon production target, respectively. PIE of the specimens will be performed at PNNL.

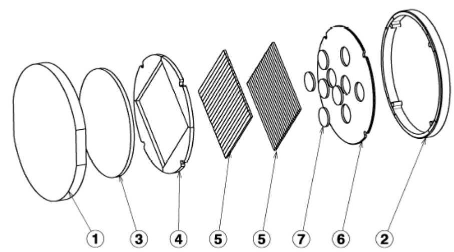

Figure 4: Silicon capsule with Si and SiC-coated graphite specimens.

Aluminum Capsule

Aluminum is the chosen material for the proton beam window at ESS. As shown in Fig. 5, two aluminum alloys (Al6061 and Al5754) and various specimen types are enclosed in a Helium filled capsule, to maintain a low peak irradiation temperature of about 70 °C. There are tensile, laser flash (for thermal conductivity measurement), TEM and luminescent coated disc specimens in the capsule, with PIE work planned at PNNL, LANL and BNL.

Component	Material	Quantity
Tensile Specimen	Al6061-T6	6
	Al5754-O	6
LFA Specimen	Al6061-T6	7
	Al5754-O	7
TEM/SP Specimen	Al6061-T6	14
	Al5754-O	14
Luminescent Coating Specimen	Al_2O_3-Cr1%	18
	Y_2O_3	6
	Activation foils	-

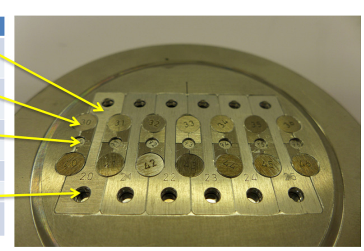

Figure 5: Aluminum capsule with various specimen types.

Titanium Capsule

Titanium is the proton beam window material at KEK and is included in this experiment to evaluate various Ti grades (Grade 5, 9 and 23) at higher radiation damage levels than has been attained so far during operation at KEK. Titanium (Grade 5 DMLS and CP) is also the candidate material for the water-filled beam dump drum at FRIB. Figure 6 shows the different types of specimens enclosed in the Helium filled capsule to achieve a peak irradiation temperature of about 370 °C.

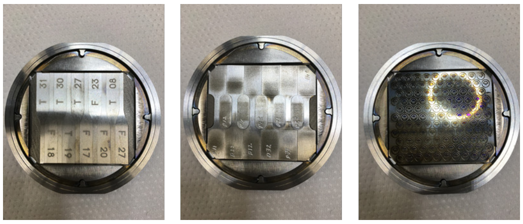

Figure 6: Titanium capsule showing fatigue (left), tensile and microstructural (middle), and meso-scale fatigue (right) specimens.

The fatigue specimens will be tested in a fatigue testing machine specifically designed to operate inside the hot cell at BNL. Tensile and microstructural specimens are also included to measure strength properties and changes in microstructure. And finally, the capsule also contains multiple meso-scale cantilever-type fatigue specimens laser-machined on a 250 μm thick foil as shown in Fig. 6 (right). These meso-cantilevers will be individually tested with an ultrasonic generator (20 kHz, 46 μm max. amplitude, 10^6 m/s^2 max. acceleration) for high cycle fatigue properties, a relatively novel technique developed by the University of Oxford. PIE work on the various specimens will be performed at the University of Oxford, BNL and PNNL.

High-Z Capsule

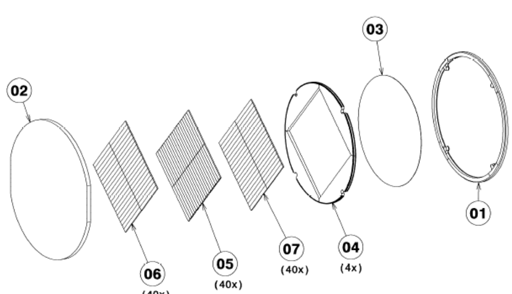

Figure 7: Ir, TZM and CuCrZr specimens in high-Z capsule.

The high-Z capsule, enclosed in vacuum, contains Iridium and TZM, candidate materials for the CERN antiproton decelerator and Search for Hidden Particles (SHiP) targets, as well as CuCrZr specimens for the SPS internal dump. Due to the high density of the materials, this capsule is only irradiated for two weeks in order to minimize the residual dose rate and stay below limits for handling and transportation purposes for PIE work at PNNL. To maintain the energy degradation of the target box, a replacement Ti capsule and vacuum degrader are inserted into the target box for the other 6 weeks of irradiation. Figure 7 shows a sketch of the bend specimen layers for the different materials.

Target Box

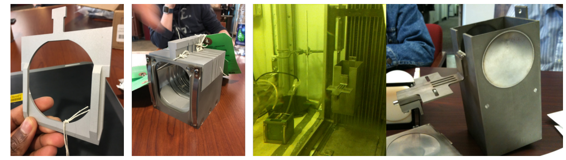

Figure 8: BLIP capsule holders, target basket and target box.

Figure 8 shows the multiple capsule holders (left), into which each capsule is inserted, as well as the target basket (middle) which houses all the capsule holders. The target basket is then inserted in the target drive box (right) which is lowered into the BLIP beam line from the hot cell.

DPA and Gas Production

The calculated peak DPA and gas production rates [5] in each of the materials included in this irradiation experiment are shown in Figs. 9 and 10.

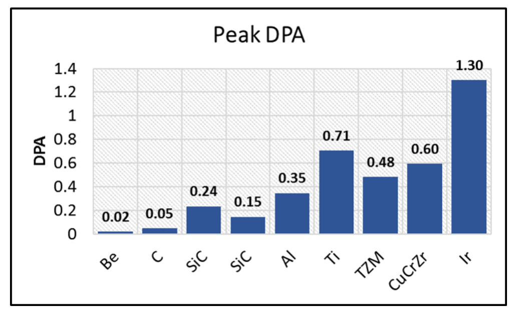

Figure 9: Peak DPA in the BLIP materials.

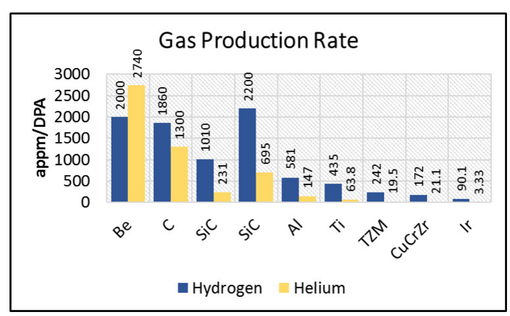

Figure 10: Peak gas production rate in the BLIP materials.

CONCLUSION

Upon completion of the irradiation campaign and sufficient cool-down time to meet Type A radioactive shipment requirements, the capsules will be shipped to the various PIE institutions. Initial PIE work will begin in early 2018.

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